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RE-1000 Free-Piston Stirling Engine Update

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
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Prepared for
Twentieth Intersociety Energy Conversion Engineering Conference
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RE-1000 FREE-PISTON STIRLING ENGINE UPDATE

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SUMMARY

A free-piston Stirling engine has been under test at the NASA Lewis Research Center test facilities. The tests performed over the past several years on the single cylinder engine were designed to investigate the dynamics of a free-piston Stirling engine. The data are intended to be used primarily for computer code validation. NASA Lewis report TM-82999 gives a description of the engine and its instrumentation. Initial test results were reported in TM-83407. Both reports are by J.G. Schreiber.

The tests designed to investigate the sensitivity of the engine performance to variations in working space pressure, heater and cooler temperatures, regenerator porosity, power piston mass and displacer dynamics have been completed at Lewis. In addition, some data were recorded with alternate working fluids. A novel resonant balance system for the engine was also tested.

This report presents some preliminary test results of the tests performed at the NASA Lewis facility along with an outline of future tests to be run with the engine coupled to a hydraulic output unit. A description of the hydraulic output unit is given.

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INTRODUCTION

A 1 kW (1.33 hp) single cylinder free-piston Stirling engine, known as the RE-1000, has been under test at the NASA Lewis Research Center for several years. The RE-1000 sensitivity test program was designed to give detailed information about the performance and dynamics of a free-piston Stirling engine. A short test program was included to test the effectiveness of a resonant balance system. Future tests will be run with the RE-1000 converted to provide hydraulic output. The hydraulic output device was designed and built to operate as a two pulse/cycle load or as a four pulse/cycle load.

This work is funded under a joint cooperative interagency agreement, number DE-AI05-81OR21005 between the NASA Lewis and the Department of Energy, Oak Ridge National Laboratory (DOE/ORNL).

This report gives a description of the range of data gathered in the sensitivity tests. Also presented is a brief description of the testing of a resonant spring mass balance system. A description of the hydraulic output unit is provided along with a discussion of tests to be run with the RE-1000 hydraulic output system.

FACILITY DESCRIPTION

A cutaway view of the RE-1000 is shown in figure 1 with key components labeled. The RE-1000 was designed and fabricated at Sunpower Inc., Athens, Ohio. It was built for NASA Lewis to be a reliable test bed for gathering data to be used for computer code validation and as a basis for the evaluation of experimental components.

The RE-1000 was designed with a displacer sprung to ground, an annular regenerator and cooler, and an electric resistance heater head. The load is provided by a dashpot built inside of the pressure vessel as shown in figure 1. The engine uses wear couples for all sliding surfaces.

When the engine was built, many instrumentation penetrations were incorporated to aid in the data gathering process. Some of the steady state engine parameters measured include the mean pressure of both the working space and the bounce space, and many gas, coolant and metal temperatures. Cooler heat rejection is monitored by measuring the coolant flow rate and using a pair of matched thermocouples wired in a differential temperature configuration for best accuracy. A more complete description of the RE-1000 engine and the data system is given in references 1 and 2.

The test facility was designed to allow flexibility in operating conditions. Variations in the heater head mean temperature, coolant temperature and the engine mean pressure level were possible. The facility also provided the option of several different gases to be used as the working fluid.

SENSITIVITY TESTS

In order to investigate the sensitivity of a free-piston Stirling engine to variations in design parameters, a sensitivity test plan was devised. The tests were designed to give engine data and performance maps of the engine for many different configurations. Two different displacers were used, one designed for relatively high engine efficiency (displacer 1), and the other designed for relatively high power (displacer 2). The displacers are described in reference 1.

Two different regenerators were used. As with the displacers, one was designed for high efficiency and the other was designed for high power. The high efficiency regenerator, number 1, had a porosity of 76.0 percent. The high power regenerator, number 2, had a porosity of 81.2 percent.

Most tests were run with the standard power piston which resulted in an operating frequency of 30 Hz at 7.0 MPa working fluid mean pressure with helium. Some tests were run with a light power piston designed to increase the operating frequency by approximately 25 percent relative to the same conditions with the original power piston. Most engine tests were run with helium as the working fluid, however, some data were recorded with nitrogen and some with argon as the working fluid.

The test configurations run and the number of data points recorded with each configuration were as follows:

Regen.	Displ.	Power piston	Fluid	No. of points
2	1	Orig	He	108
2	2	Orig	He	190
1	1	Orig	He	151
1	2	Orig	He	176
1	1	Orig	Ar	12
1	1	Orig	N_2	64
1	1	Light	He	84

With each configuration listed above, the engine was tested over the map shown in figure 2. The total number of data points recorded in the sensitivity tests was 785. The detailed data recorded will be published in a future report.

Part of the data recorded in the tests was the dynamic pressure drop of the heat exchangers. Differential pressure transducers were close coupled to measure the pressure drop of the cooler, the regenerator and the complete heat exchanger loop. This data was measured with Validyne differential pressure transducers and will be published with the rest of the data.

BALANCE SYSTEM

As part of the Space Power 100 kW (SP-100) program, Sunpower Inc., designed a resonant spring mass balance system for the RE-1000. The balance system is shown in figure 3. The system was designed to counteract the engine's inherent vibration at 30 Hz. Small additional masses made it possible to adjust the resonant frequency of the balance system by ± 0.5 Hz.

Figure 4 shows the results of the balance system tests. The test was conducted with the power piston operating at a stroke of 2.5 cm. The frequency was varied by changing the engine mean operating pressure. As can be seen in figure 4, the balance system dramatically reduced the engine vibration level when the engine is operated at the design point of the balance system.

HYDRAULIC OUTPUT UNIT

As part of the NASA Lewis free-piston Stirling engine program funded by DOE/ORNL, a hydraulic output device was designed and built for the RE-1000. The detail design work and the fabrication of the system was done by Foster-Miller Inc., of Waltham, Mass. As with the original design of the RE-1000, the hydraulic output device was designed to be a rugged test bed to be used as a research tool. The unit features modular design for flexibility of test configurations, ease of instrumentation, balanced or unbalanced operation, and two or four pulse/cycle pump configurations.

To convert the RE-1000 engine from the dashpot load to the hydraulic load, the power piston, power piston cylinder, the dashpot load and the pressure vessel were removed. The power diaphragm, shown in figure 6 along with its supports, is attached to the engine such that the compression space gas pressure acts on one side of the diaphragm. On the other side of the diaphragm is the hydraulic system. The power diaphragm assembly is shown in figure 7, looking at it from the hydraulic side. The hydraulic fluid displaced by the power diaphragm acts against one face of the pump rod piston. The pump rod assembly is shown in figure 8. While the oil below the pump rod piston supplies power to the pump rod from the power diaphragm, the oil above the pump rod piston acts against the bounce space diaphragm.

The balance system for the hydraulic output device is shown in figure 5 as masses M_2 and M_3. In figure 8, M_2 is shown attached near the midpoint of the pump rod and M_3 is shown to the left of the pump rod. During operation of the hydraulic output device, M_2 and M_3 will move in opposite directions due to the pumping action of M_2 and the hydraulic fluid in the balance system. If it is desired to operate the engine without the balance system, M_2 is removed from the pump rod and M_3 is eliminated. The mass shown on the right side of figure 8 is then clamped on the pump rod to maintain the same oscillatory mass and therefore the same resonant frequency as with the balance system.

The top of the pump rod extends into the pump body. The pump body and the inlet and outlet check valves are shown in figure 9. The pump has two features that make it ideal for this application; a null band to assure system stability and a buffer diaphragm to convert the hydraulic pump into a two pulse or a four pulse per cycle pump.

A plot of the hydraulic load is shown in figure 10. The existence of the null band causes the load curve to have a greater slope. At the match point of the engine power output and the load power absorbed, the system now has much better stability since the power output curve and the load curve cross at a more severe angle. The null band can be seen in figure 11. Since the hydraulic fluid is incompressible, the lower pump chamber will be able to do some pumping work when the piston is moving in the upper pump chamber. Likewise, the upper pump chamber can do work while the piston is moving in the lower pump chamber. This arrangement shown in figure 11 is the four pulse per cycle configuration because it has four inlet pulses and four output pulses per cycle.

The two pulse per cycle configuration is shown in figure 12. In this configuration a small accumulator is connected to the ports inside the pump that form the null band. Because the accumulator is not a rigid device and therefore can change volume, the chamber of the pump that is connected to the null band cannot do pumping work. It will merely expand or compress the accumulator.

The hydraulic output device is shown partially assembled in figure 13. The small accumulator used to convert the device to a two pulse/cycle pump can be seen attached to the pump body near the top of the device. The other small accumulator attached to the pump body is used to buffer the pump output and convert the pulsed flow into a smooth flow. A similar buffer is also attached to the opposite side of the pump to smooth the inlet flow. Above the pump body is a linear variable-differential transformer (LVDT) used to measure the pump rod position. The cylindrical section below the pump body is the balance cylinder inside of which the annular balance piston oscillates. Figure 14 shows a cutaway view of the hydraulic output device with key parts labeled.

The free-piston Stirling engine hydraulic output system is controlled by a Kaypro 2 computer and a Starbuck microprocessor. The purpose of the control system is to check the center positions of each of the oscillating members. If at any time the center position of the pump rod or of the diaphragms drifts too far from the design position, the control system will activate the appropriate valve to correct the situation. The layout of the valves can be seen in figure 5. The software in the Kaypro has the ability to do limit checking for safety purposes and also has routines for automatic start up and shut down.

TEST PLAN

Due to the modular design of the hydraulic output device and the ease with which instrumentation can be installed, the RE-1000 is an ideal research tool. The main emphasis of the research to be done on the hydraulic system is to characterize the interaction between the engine and the load. To do this, the pump configuration will be altered to vary the characteristics of the load. The pump can be changed between a two pulse/cycle and a four pulse/cycle pump as was described before. By adding other hardware, the hydraulic pump can be made to have a greater spring content to act more similar to a compressor than a pump.

The hydraulic device also has the capability to use a different gas in the bounce space than the gas used in the working space. With this ability, an investigation of hysteresis in gas springs can be performed.

CONCLUDING REMARKS

During years of test runs, the RE-1000 has proven itself to be a rugged and reliable test bed for free-piston Stirling engine research. Any failures in hardware that did occur were traced to improper assembly (twice) or were failures of instrumentation. The engine has accumulated nearly 300 hours of operation to date.

The data collected during the sensitivity tests are currently being processed. A report will be published at some future date to present the detailed data. These data should provide a base for computer code validation.

The RE-1000 is currently being converted into a free-piston Stirling engine-hydraulic output system. Research on engine load interaction will soon be initiated. The design intent of the hydraulic output device, as was the design intent of the original engine, was to make a rugged, reliable, well instrumented research tool.

REFERENCES

1. Schreiber, J. "Testing and Performance Characteristics of a One kW Free-Piston Stirling Engine." NASA TM-82999, 1983.

2. Schreiber, J. "Test Results and Description of a One kW Free-Piston Stirling Engine With a Dashpot Load." in, Energy for the Marketplace, IECEC '83, Vol. 2, AICHE, New York, 1983, pp. 887-896.

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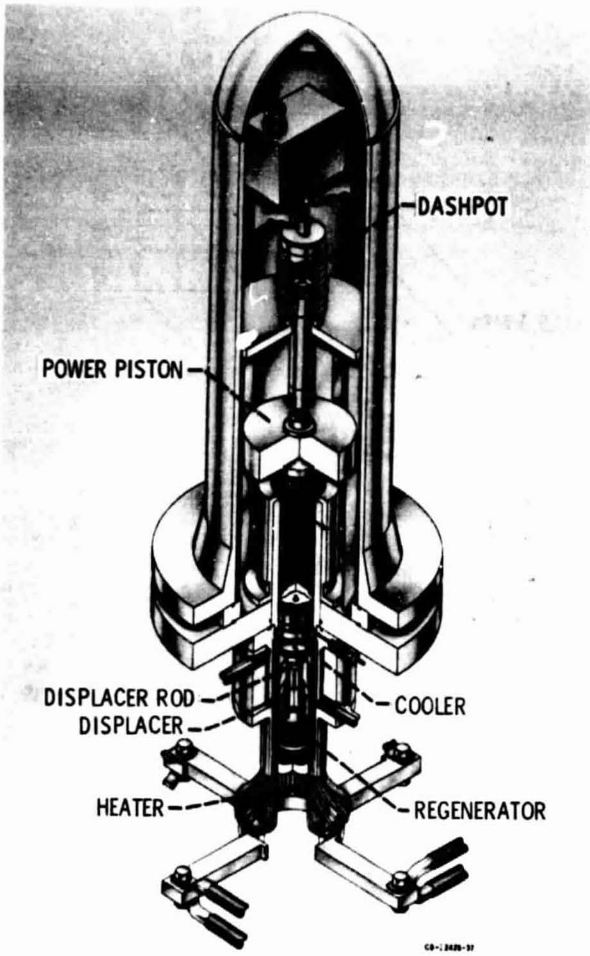

Figure 1. - Cutaway view of RE-1000 free-piston, free displacer Stirling engine.

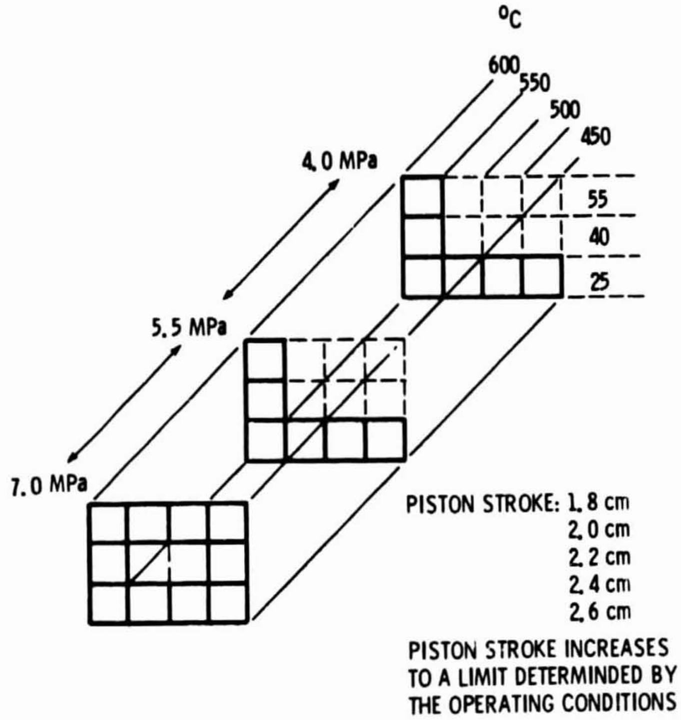

Figure 2. - RE-1000 test matrix.

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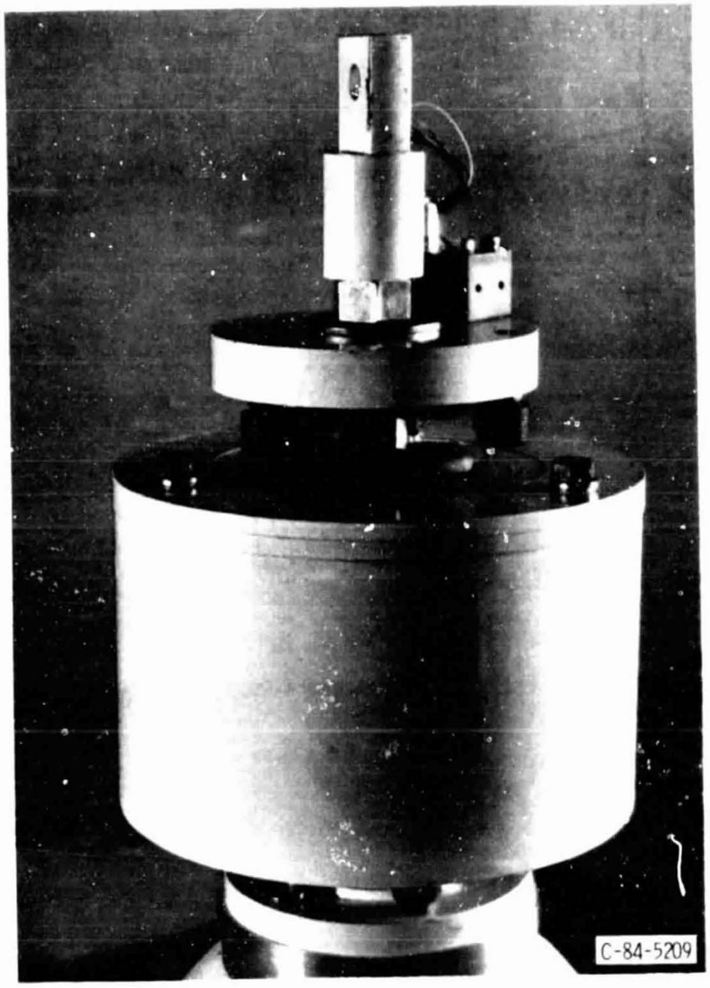


Figure 3. - Balance device on top of RE-1000

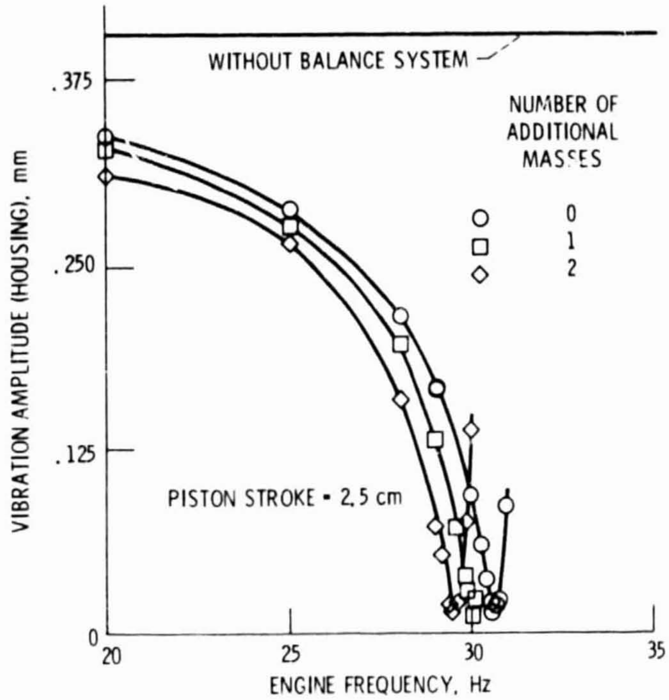
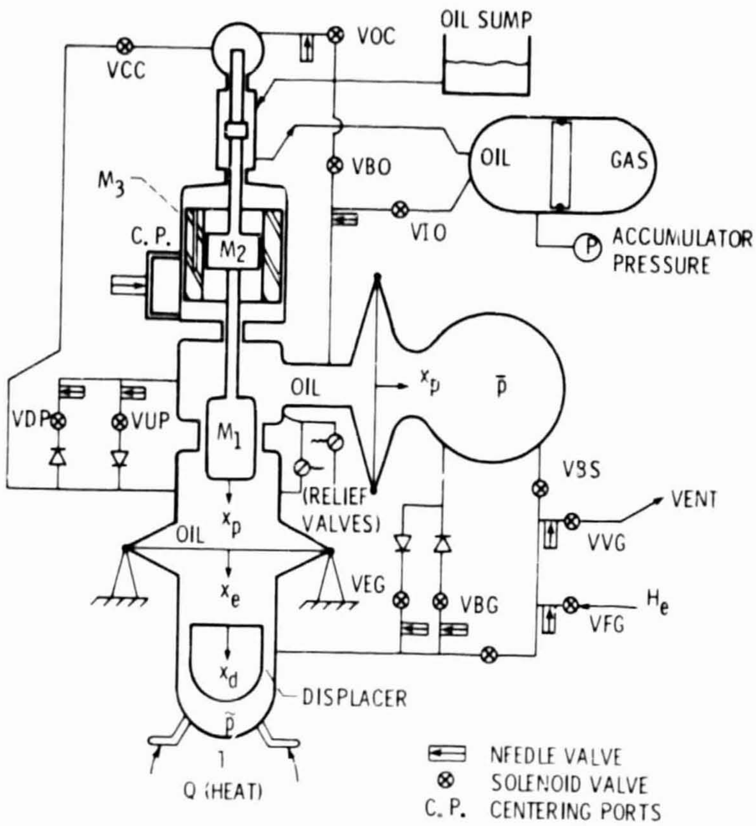


Figure 4. - Engine vibration amplitude versus frequency.



VBG, BOUNCE GAS INCREASE
VBO, BLEED OIL
VBS, BOUNCE GAS SERVICE
VCC, CLOSE TO COCK
VDP, DOWN PISTON MOTION
VEG, ENGINE GAS INCREASE
VES, ENGINE GAS SERVICE
VFG, FILL GAS
VIO, INJECT OIL
VOC, OPEN TO COCK
VUP, UP PISTON MOTION
VVG, VENT GAS

Figure 5. - Hydraulic output device schematic.

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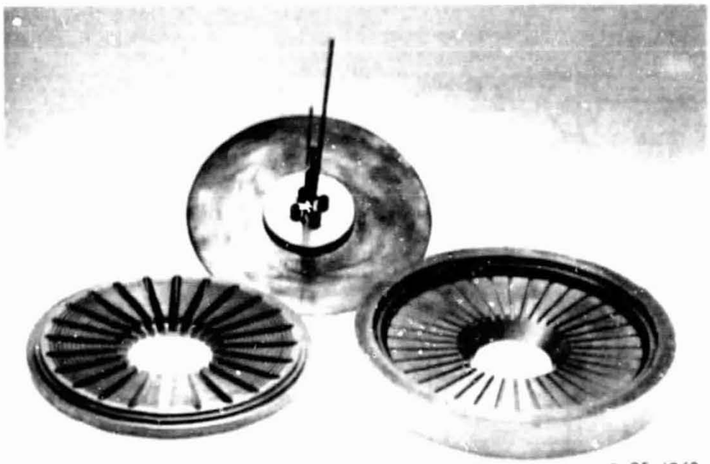

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Figure 6. - Hydraulic output device Power Diaphragm.

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Figure 7. - Hydraulic output device Power Diaphragm Assembly.

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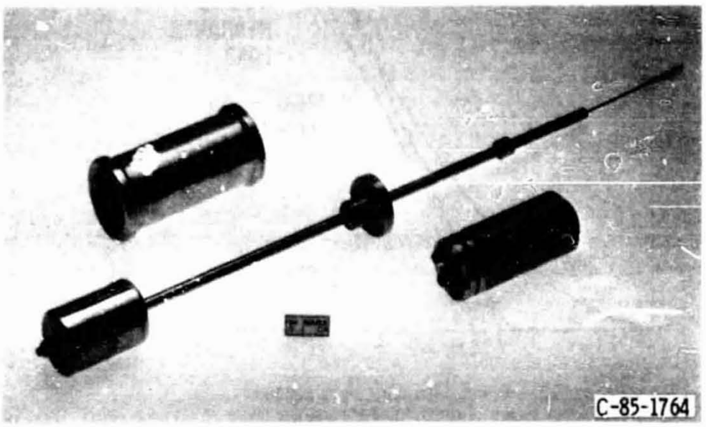

Figure 8. - Hydraulic output device Pump Rod.

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Figure 9. - Hyraulic output device Pump Housing.

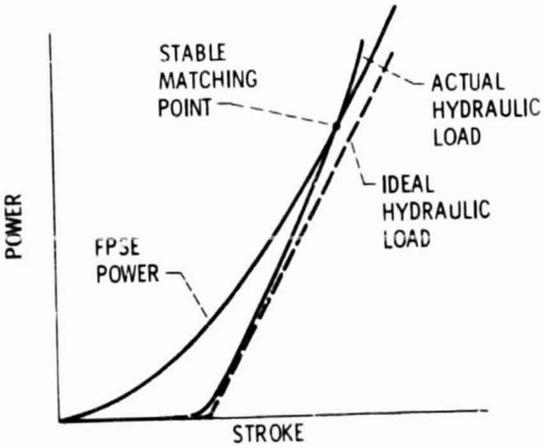
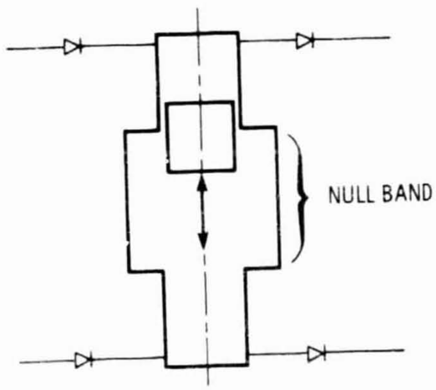
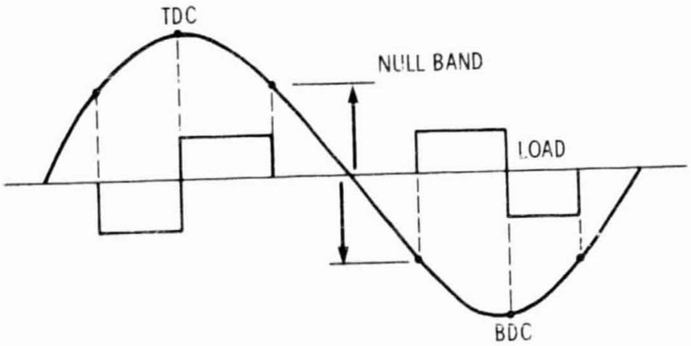


Figure 10. - Power load matching between engine and hydraulic output device.

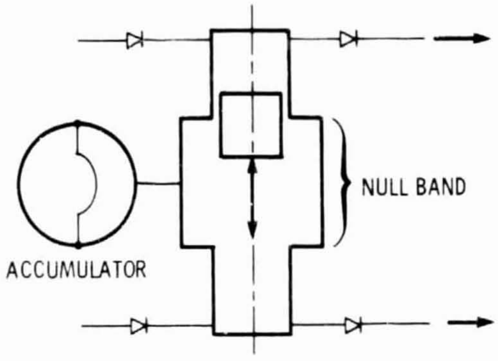


(a) Pump schematic.

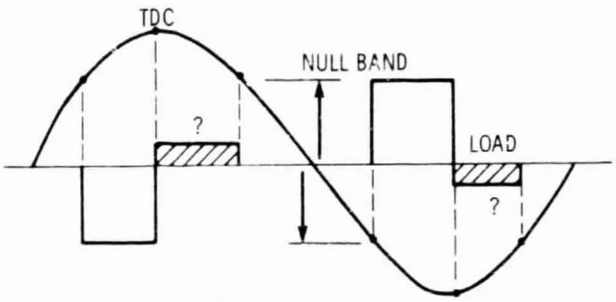


(b) Motion and load versus time.

Figure 11. - Double acting 4 pulse per cycle pump.



(a) Pump schematic.



(b) Motion and load versus time.

Figure 12. - Double acting 2 pulse per cycle pump.

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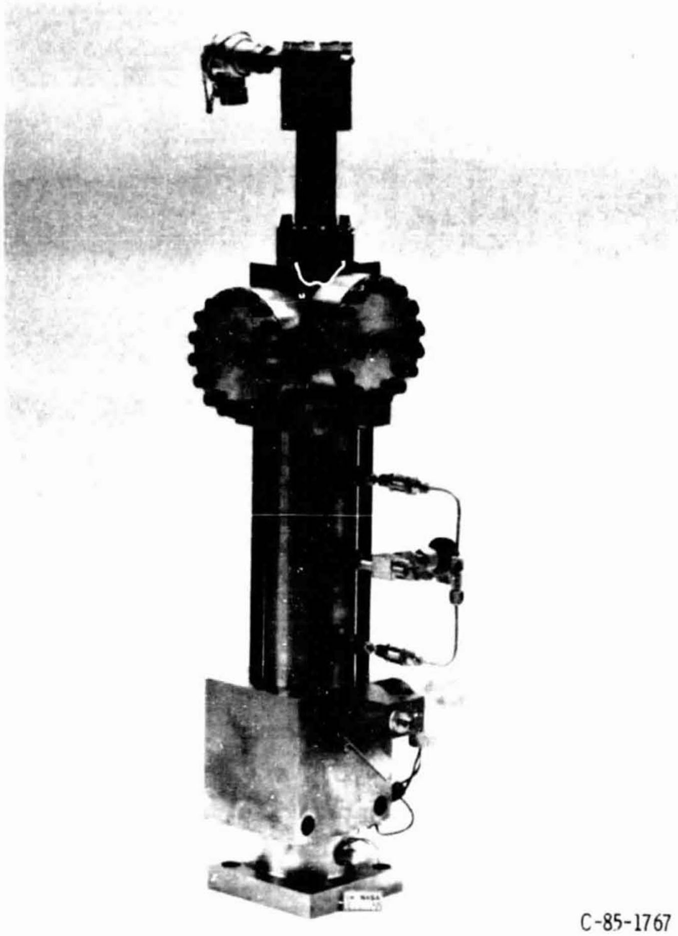

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Figure 13. - Partial assembly of Hydraulic Output Device.

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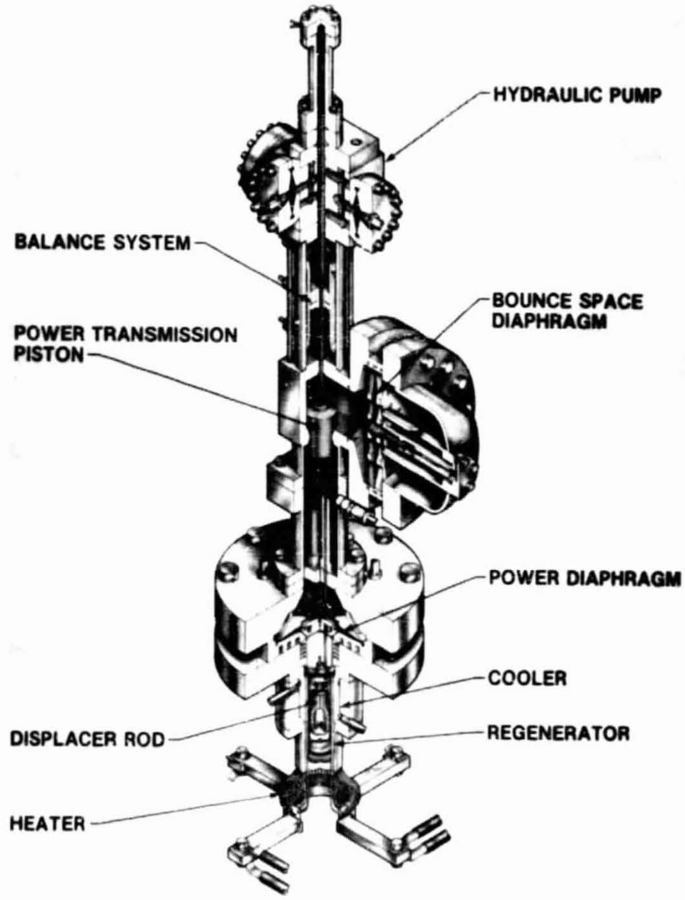

Figure 14. - Cutaway view of the RE-1000 Free-Piston Stirling Engine with hydraulic load.

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16. Abstract

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